MICROWAVE MAGNETRONS: A BRIEF HISTORY OF RESEARCH AND DEVELOPMENT

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In this history of the evolution of the magnetron, the essential steps in the transition from the first glass envelope magnetron device to the copper block design are briefly outlined. These are followed by short accounts of the main stages of elaboration which have led to present day magnetrons. In view of the vast range of application and the tremendous effort deployed on development during wartime and following years, attention has been concentrated on basic design steps and overall performance, with little attention to detailed performance.

EARLY STEPS

The present day magnetron is the result of extensive researches and developments under the stimulus of defence requirements. However, it originated from the research by Hull in the USA to resolve a patent dispute. In 1921 he invented the magnetron diode[1]. In this, an axial magnetic field provided the means to control the current passing through a smooth bore cylindrical coaxial diode by bending the electrons away from the anode, figure 1(a). It was developed as an audio amplifier and r.f. source but, following the resolution of the dispute, was no longer needed, and development ceased.

In 1928, Zacek showed that oscillations could be produced in the simple diode at the critical (cut-off) magnetic field with a frequency close to the cyclotron frequency[2], that is, the angular frequency of rotation of an electron around a magnetic field.

In 1924, Habann had described a split anode system producing negative resistance oscillations[3]. In this, variation of potential of either anode segment, with a magnetic field greater than the 'cut off' value, results in a greater current flowing to the lower potential segment than that to the higher potential segment, figure 1(b). Thus the magnetron behaves as a negative resistance to a circuit connected across the segments, and oscillations can be produced over a wide range of frequencies below those for which electron transit time is significant.

In 1929, Okabe published Japanese work using a split anode system to generate centimetre waves[4]. This attracted world wide interest in the practical possibilities of the magnetron and from 1933 onwards a steady stream of workers in Europe, Russia, Japan and America developed both practical and theoretical ideas on the use of the magnetron for short wave generation. Among these was Megaw of the GEC Research Laboratories at Wembley[5].

Use of multi gap anode

Comparison of performance obtained by different workers, who did not have the means of rapid contact enjoyed today, was made difficult by the various possible 'electronic' and 'circuit' modes of oscillation. However the successful development by Postumus in 1934 of a 4-segment magnetron, figure 1(c), and the rotating field theory by which he explained its advantage over a similar 2-segment system[6], was a major step forward which anticipated later theoretical work, and showed the advantage to be gained by the use of a multiplicity of anode segments in reducing the magnetic field at which a given efficiency could be obtained.

First use in system

As an example of the state of application of the 4-segment magnetron in 1937, figure 2, shows the valve developed at GEC, Wembley, for operation in the range 40–60 cm and used in the circuit shown schematically whilst figure 3 shows the complete transmitter of a communication equipment for use at sea, also developed at Wembley[7]. This was for studies of the problem of secure communication at centimetre wavelengths. In view of the need for frequency stability, the equipment was fitted with a coaxial resonator, by means of which the frequency was stabilized and could be switched as needed for operational reasons, and the anode voltage was stabilized. The power produced was 20 W at about 1000 V and modulation was by square wave switching of the anode voltage. Twelve sets of the equipment were made by GEC Telephone Works and most of these had been fitted on HM ships by the time World War 2 started.

This work was carried out, of course, with the closest possible cooperation of the Admiralty, and especially with officers of HM Signal School at Portsmouth. Together with other special work on valves for the Air Ministry, it led to the appointment of C. C. Paterson, Director of the GEC Research Laboratories, as Chairman of the Government Inter Services Valve Technical Committee (later CVD). This initiated the close relationship that has been maintained at the highest levels between the valve interests of the GEC and those of the Defence Services.

Large cathode

An important factor in the rapidly growing development of the magnetron was the diameter of the cathode which from the earliest days had been kept small (about 3% or less of the anode diameter). In 1939, in the course of discussions between Megaw

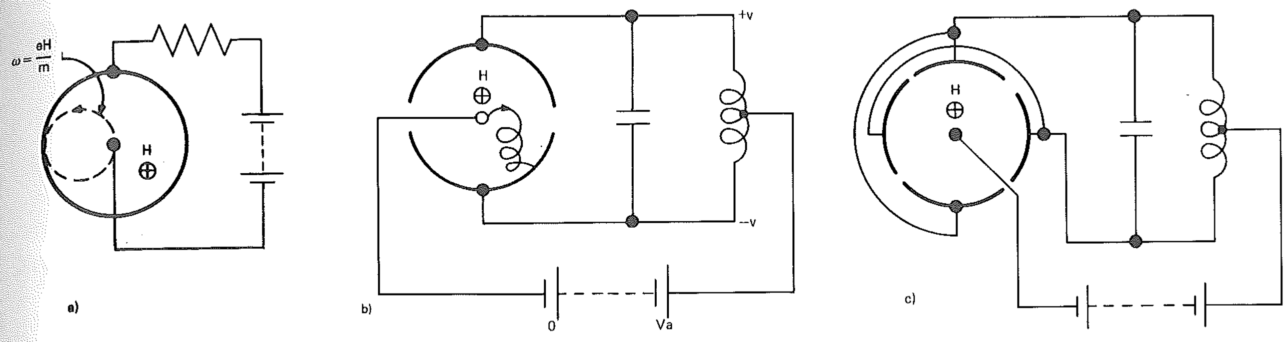


Fig. 1. Some early experimental magnetrons (a) Hull, 1921 and Zacek, 1928 (b) Habann, 1924 (c) Postumus, 1934

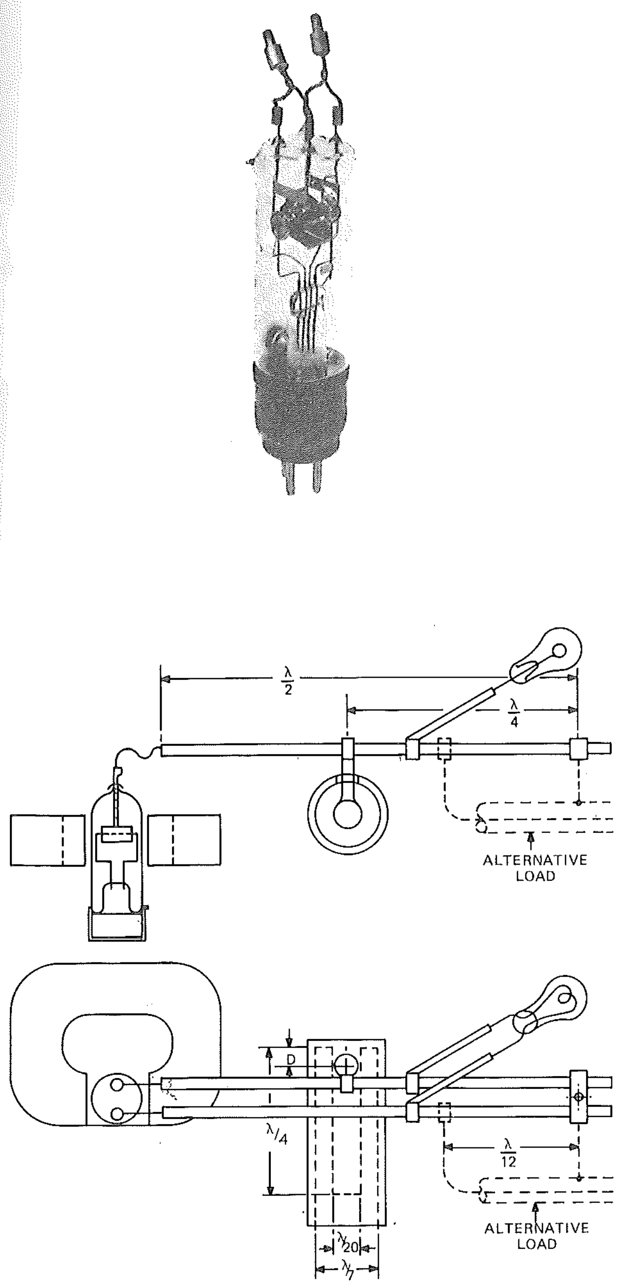


Fig. 2. Magnetron valve and circuit used for communications transmitter, 1937

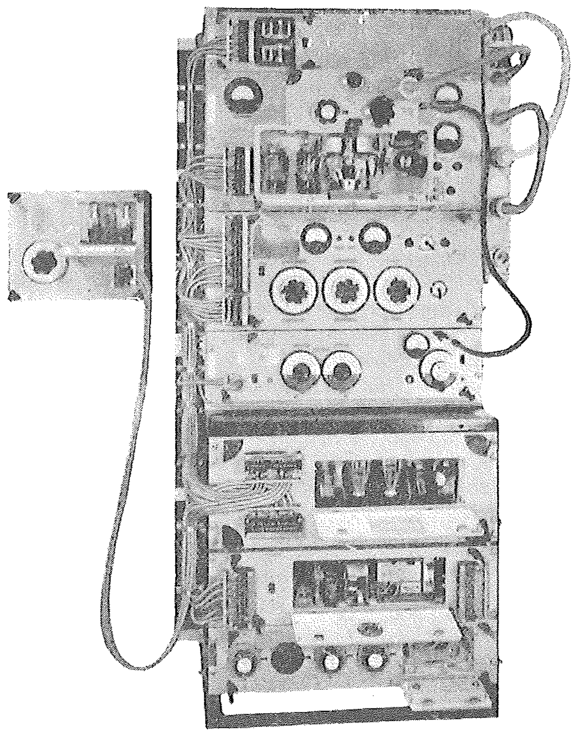


Fig. 3. Communications transmitter, 1937

and Gutton of SFR in Paris, it was concluded that a much larger cathode might be used in multi-segment valves without loss of efficiency. It was agreed that samples of the M16, Gutton's 8-segment resonant segment valve, figure 4, should be fitted with large cathodes, and sent to this country.

COPPER BLOCK ANODE

Shortly afterwards, Megaw made contact with Randall and Boot at the University of Birmingham, when it was disclosed that a 6 gap copper block magnetron operating at 9.9 cm wavelength had been made[9], having a tungsten filament cathode of diameter about 6% of that of the anode, and giving an output (c.w. or pulsed) of 150 watts. This made use of 6 resonant circuits machined out of a solid copper block forming the anode, figure 5(a), through the centre of which a wire cathode was mounted. Power was extracted through a concentric line coupled to a

loop in one of the cavities. The valve was continuously pumped and was operated in an electromagnet, figure 5(b).

Design of unstrapped valve

Megaw immediately designed a sealed-off version with improvements resulting in a considerable reduction of the 50 lb magnet weight, and substantially repeating the performance of the Birmingham valve. He then decided to improve the design further by incorporating a large diameter thoriated tungsten spiral cathode, and reducing anode length so that an existing 6 lb permanent magnet could be used. All this was done under the stress of wartime pressure.

At this point, in May 1940, samples of the French M16 were brought to Wembley. As agreed, they had been fitted with large diameter oxide coated cathodes and tests showed a pulse power of the order of 1 kW at 16 cm wavelength, with efficiency up to 15%. Accordingly it was decided to incorporate both thoriated tungsten spiral cathodes and oxide coated cathodes in the Wembley design of large cathode valve. Both were completed together and showed similar results, an output of the order of 1 kW peak being obtained at 5–40 μS, 50 p.p.s. at 9.8 cm wavelength using a 5 lb permanent magnet, figure 6(a). This was on June 29, 1940. Within a fortnight, an output of about 10 kW had been measured in a water load, using the higher magnetic field of an electromagnet. After detailed measurements, it was decided to modify the design so that the higher power could be obtained with the lower field permanent magnet. The number of segments was accordingly increased from six to eight. Figure 6(b) shows a section of this valve which was standardized for Naval use at around 10 cm wavelength. This was the NT 98.

A copy of this was sent to the USA in August, 1940. A variant operating at 9.1 cm was then produced for the first centimetric airborne interceptor (AI) equipment for airborne use.

As soon as the design requirements for valves capable of meeting operational requirements had been established, contact was made with the BTH Research Laboratories at Rugby, where work had been proceeding on high power klystrons. As a result, effort was transferred to the development of the copper block magnetron and its production. This contact between GEC and BTH groups was maintained until long after the end of wartime.

A number of teams were set up at Wembley to construct magnetrons needed by the Services and to study their performance since experience in use showed defects limiting system performance. Nevertheless, large numbers of valves of this and later types were produced in the laboratories, allowing time for factory production facilities to be established elsewhere.

This design was the basis for a range of magnetrons produced in this country and in the USA with little change in constructional details. From this time, very close contact was maintained with the USA, resulting

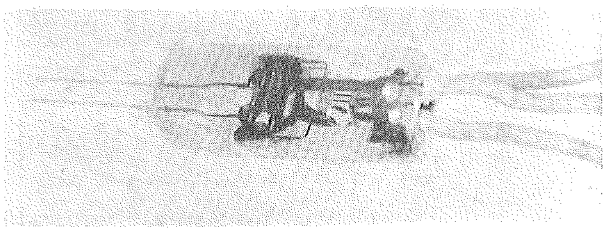
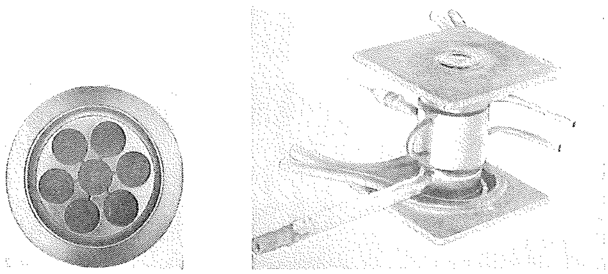
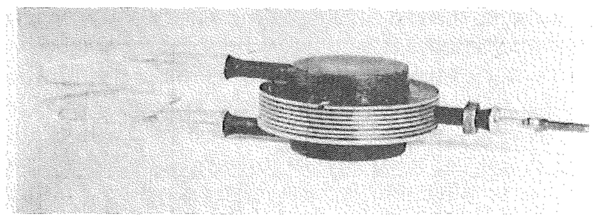


Fig. 4. Gutton resonant – segment magnetron, type M16, 1940

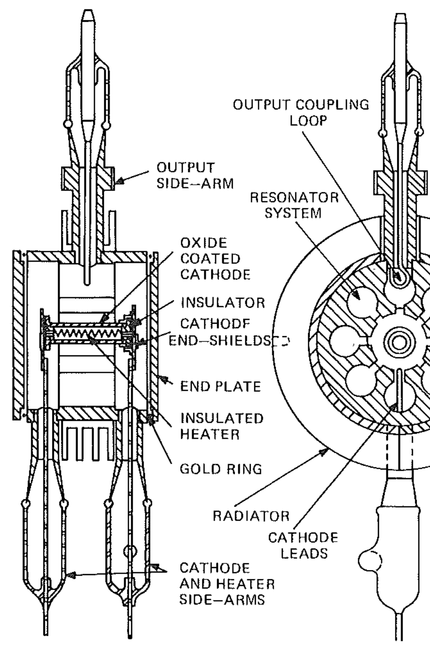


a) b)

Fig. 5. (a) The anode block of (b) the first British 10 cm magnetron



a)



b)

Fig. 6. (a) Magnetron type E1189, the original design for operation in aircraft (b) magnetron type NT98

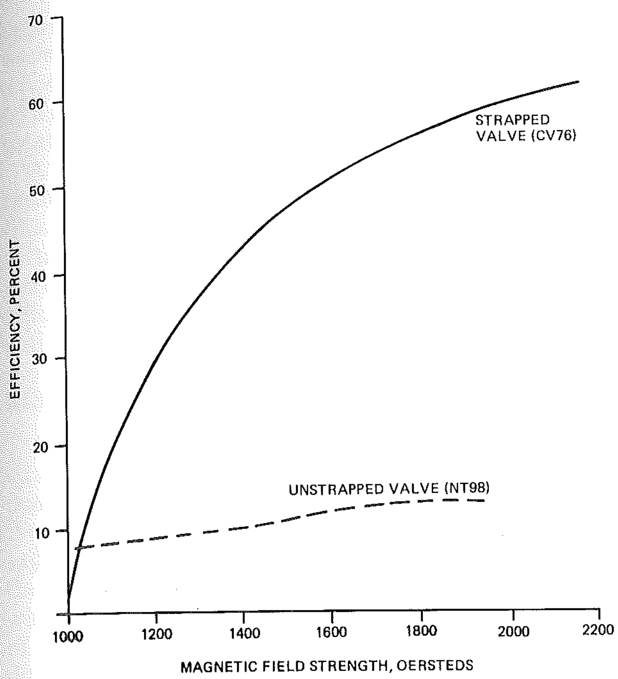


Fig. 7. The effect of strapping on efficiency

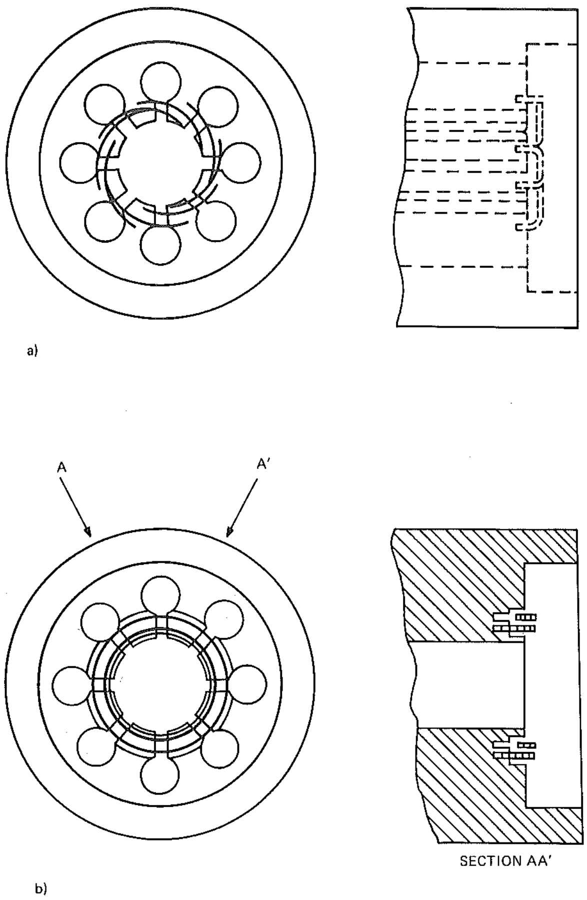


Fig. 8. Methods of strapping (a) echelon strapping (b) double ring strapping (recessed). The same system is used at both ends of the block

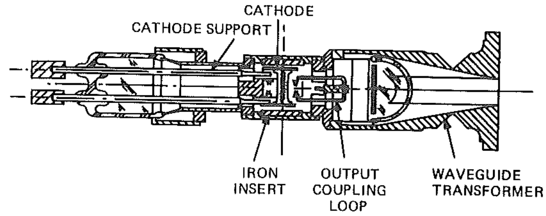


Fig. 9. Section through high power 3 cm magnetron, type CV355

in many new design and constructional features being transferred to this country as the very large American effort developed.

STRAPPING

Experience in the use of this early design showed that with change of r.f. load or operating conditions, the frequency generated could change discontinuously. In 1941, Sayers of the University of Birmingham showed that this resulted from the excitation of the different modes of resonance of the multi-cavity anode in which successive cavities operated with phase differences less than the optimum value of π. He showed that by joining alternate segments together by wires, stability and efficiency were greatly improved[(9)]. In the NT 98 magnetron, for example, the efficiency had seldom risen above 25% even at high magnetic field, whereas by this technique, an efficiency of 40% could be obtained at a magnetic field of 1500 oersteds and 50 to 60% at 2000 oersteds, figure 7. This established the technique of 'strapping' as a necessary design feature, and various forms were incorporated in established designs as soon as possible. Figure 8 shows two forms of strapping[(10)].

DESIGN FOR 3 cm OPERATION

Work at wavelengths shorter than 10 cm started soon after the NT 98 was established, but during 1941 there was urgent need for operation around 3 cm. Early designs were based on the established unstrapped 10 cm valves but the increased number of cavities necessary to provide the required cathode area led to increased problems with mode change and efficiency[(10)]. With a 12-slot 10.5 mm anode and magnetic field of 2670 oersteds, efficiencies up to 20% were obtained with 150 kW input power, but stability problems were numerous. However, experience with smaller strapped valves showed that efficiencies of 30–40% could be obtained at the same input level with an anode of 8.0 mm diameter, with complete freedom from mode change. Figure 9 shows the main features of a 3 cm high power valve. It has a power output of at least 200 kW with efficiency of 40%, operating at 22 kV, 23 A. The anode has 14 cavities double ring strapped and it operated in a magnetic field of 5500 oersteds, obtained from an external magnet, with iron inserts inside the valve envelope. Power is radiated from a loop connected to the straps, with the output waveguide enclosed by a glass dome.

Developments at 3 cm involved not only scaling down dimensions in proportion to wavelength but also increasing the magnetic field, approximately inversely as the wavelength, leading to the need to reduce the magnetic air gap. This was done in the USA by building in pole pieces at each end of the anode block, and attaching 'C' shaped magnets to each end. The cathode was supported at one end through a hole in the pole piece resulting in the 'packaged' valve of figure 10. This packaged arrangement became the standard for 3 cm valves, both for low and high power.

PERFORMANCE OF PRODUCTION TYPES BY 1945

The performance achieved by 10 cm types may be summarized as shown in table 1[10]. These operated with pulse lengths of 1 to 2 μS and repetition rates of 500 to 1000 pps.

The number of types established in production for 3 cm operation was much less than for 10 cm. First, unstrapped designs were produced, to be followed by strapped designs as the increased complexity was mastered. All operated at around 14 kV, with efficiencies in the range 20–40%, with 1 μs pulses at 1000 p.p.s. (typically). An external magnet was used. Coupling to the output waveguide was from a glass enclosed probe coupled to the 'preplumbed' section of waveguide, as in the CV 214 illustrated in figure 11.

MECHANISM OF ENERGY TRANSFER

Once the success of the multi-cavity design had been demonstrated, a considerable theoretical effort was applied, especially at the Universities of Manchester and Leeds and at MIT in the USA to try to understand the parameters of importance in design. In combination with the results of experimental work, the picture eventually emerging was as follows.

When the valve is oscillating in the so-called 'π mode' with the currents in adjacent cavities in antiphase, a standing wave of potential exists round the anode. This may be considered as made up of oppositely rotating travelling waves of angular velocity w/n where n is the number of pairs of segment gaps.

Electrons leaving the cathode under the influence of mutually perpendicular electric and magnetic fields, travel around the cathode with velocity

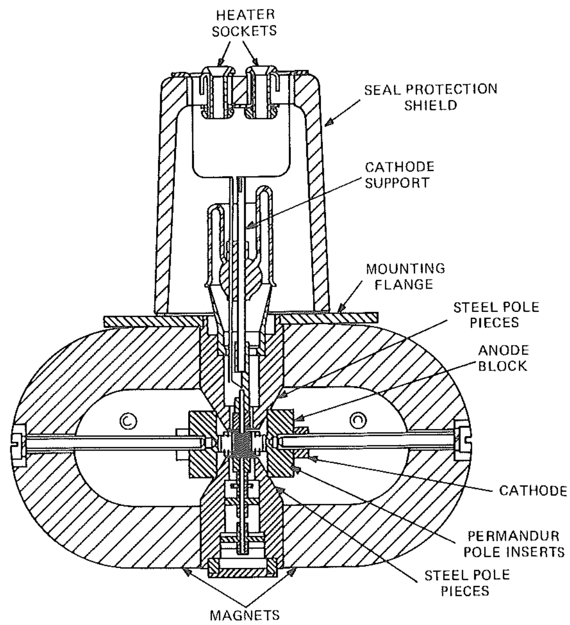


Fig. 10. Section through magnetron type CV348

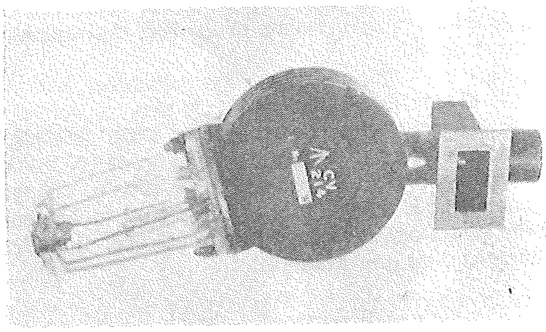


Fig. 11. Magnetron type CV214

TABLE 1

Performance of 10 cm magnetrons

	Wavelength cm	Input (peak) kW	Input (mean) W	Efficiency, %
NT 98 (unstrapped)	10	75	38	10
CV 56	10	225	225	40
CV 76	10	1000	1000	50
CV 99	8.5	1000	250	50
CV 64	9.1	130	330	30
CV 192	9.1	600	480	40
CV 69	9.1	1000	250	50
V 160	9.8	500	500	50
CV 41 (unstrapped)	10.7	1000	500	15
CV 120	10.7	1000	500	35

approximating to the ratio of these fields. Providing wave and electron velocities are approximately equal, continuous energy interaction results in a transfer of energy from the static electric field to the rotating r.f. field and thence to the load.

At suitable high magnetic fields, high efficiency results, as it does with a large number of segments, though this leads to the need for special attention to the mode problems which can result. The great attraction of the magnetron has always been the high efficiencies obtained in a 'simple' diode structure, with its resulting compactness.

RISING SUN DESIGN

As the working frequency of magnetrons increases, strapping becomes increasingly impractical. The need to avoid mode change problems other than by the use of strapping led to the invention of the 'rising sun' anode, of section shown in figure 12[11]. In this, the usual system of equal cavities is replaced by one with two sets of cavities of different size, by means of which the desired separation of frequencies of the different modes, as well as operating voltage, may be achieved. Such a system is particularly suited for shorter wavelengths, especially since it avoids the use of small delicate straps and because it makes the use of a large number of cavities more practicable. Valves using this arrangement were developed during the latter part of 1945, demonstrating their potential for shorter wave operation, especially for millimetre waves.

In the AX9 of 18 cavities operating at 3.1 cm, a pulse power of nearly 1 MW was achieved, with mean power around 240 watts. In the design shown in figure 12, output power was taken from the back of one of the cavities by a slot, coupled through a slot output transformer into a vacuum enclosed output waveguide. This waveguide output system has been used in many other designs.

LONG ANODE DESIGN

Around 1950, the need arose for a valve of much greater mean power at 10 cm wavelength than then available (approx. 500 watts) and attempts were made to meet this by designing strapped valves operating at higher voltages, around 40 kV. However the power limit set by electron bombardment of the cathode led to a different approach by Boot at SERL Baldock, resulting in a design known as the 'long anode' valve[12]. In this, anode and cathode length, normally kept less than half an operating wavelength, were greatly increased to avoid the cathode power limitation. Problems of mode change were avoided through the use of a symmetrical output system and very careful design to avoid the effect of axial modes. An anode length of about a wavelength was used. The symmetrical coupling to the output system was achieved by coupling the ends of alternate cavities together to a common probe, which radiated to the output waveguide. The long anode necessitated a solenoidal magnet, so that magnet, magnetron, and waveguide were designed as one unit.

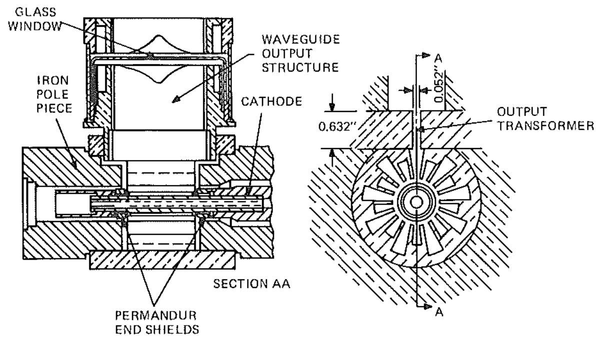


Fig. 12. Cross-sections of AX9 magnetron

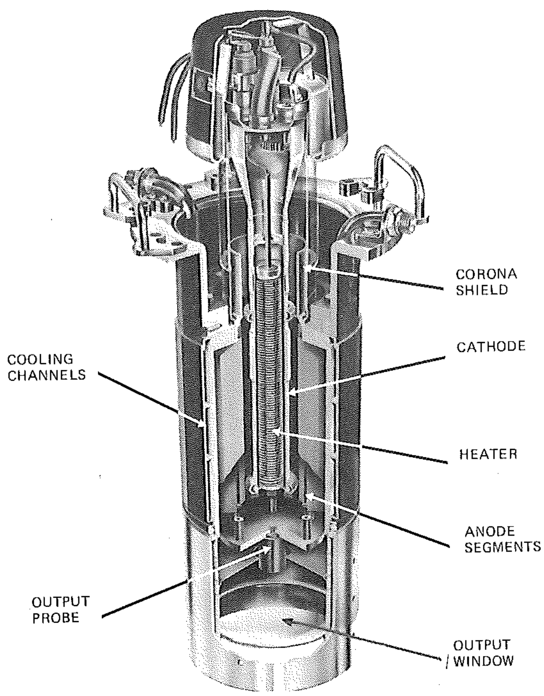


Fig. 13. Magnetron M565, giving 5 MW output in frequency range 1215–1365 MHz

Using these ideas, the design was developed and finally engineered by the English Electric Valve Company to give a power at 10 cm wavelength of 5 kW mean, 2.5 MW peak at 2 μs and 5 μs pulse length, operating at 50% efficiency with a voltage of 40 kV. Figure 13 shows a design for 23 cm wavelength, 30 kW which was also demonstrated.

COAXIAL DESIGN

In the early 1950s, it was clear that in spite of the attraction of the magnetron as an efficient, compact high power source, residual problems of stability against mode change needed to be overcome if the full potential were to be achieved, especially at shorter wavelengths. The structure now known as the 'coaxial magnetron' was devised by Feinstein and others. In this design the currents in alternate cavities were locked in phase by strong coupling to a surrounding resonant coaxial cavity, whose frequency

could be adjusted by change of length[13]. Such a system, shown in figure 14, proved very successful, though the coupling to an additional multi-mode cavity results in additional possible modes of operation, which were controlled by resistive damping. The design was particularly suited for operation at the highest frequencies and resulted in higher efficiencies and lower pulling and pushing figures. At 10 GHz, a power of 1 MW was obtained with an efficiency of 65% and a tuning range of 12%, with 100 kW at 50 GHZ. This system is especially suited for rapid mechanical tuning.

C.W. OPERATION

Although attention has been concentrated here on valves for pulsed operation, designs have also been developed for c.w. use for communication and counter measures. Though operated at much lower voltages they have given mean powers of the same order as the pulsed designs. They have been fitted with tuners operating by changing the effective dimensions of the cavities, and covering a range of 10% and upwards.

RUGGED LOW POWER

Apart from the steady increases in power generated at a given wavelength, there have been striking advances in the performance of low power rugged valves. These follow improved understanding of the factors controlling speed of oscillation build up, and the introduction of new magnetic materials and techniques of mechanical design. Such valves are needed for missile, beacon and guidance systems demanding use under conditions of extreme vibration and shock. Figure 15 shows the general design of a 3 cm valve, one of a range developed by the M. O. Valve Company Ltd. It develops 5 W mean output (150 W peak) having a mass of only 50 g and volume of 10 ccs. It operates at 850 V with 16% efficiency. It has a warm up time of only 2 secs and satisfies many stringent performance requirements.

MILLIMETRE WAVE VALVES

With the establishment of rising sun and coaxial designs, the major problems in operation were overcome, and the way was open to reducing operating wavelengths to a few millimetres. However, problems of steeply rising atmospheric and rain absorption at wavelengths much below 1 cm inhibited the use and development of millimetre radar and valves. Nevertheless, the narrow aerial beams readily obtainable coupled with use under conditions where the effect of atmosphere absorption is not overriding, has led to development down to a few millimetres. Figure 16 shows a production valve for 3.3 mm having a peak output of 2.5 kW (1.25 W mean). It operates with 50 ns pulses (down to 4 ns) at an efficiency of 4%. It has an integral samarium cobalt magnet and a weight of 2 lbs.

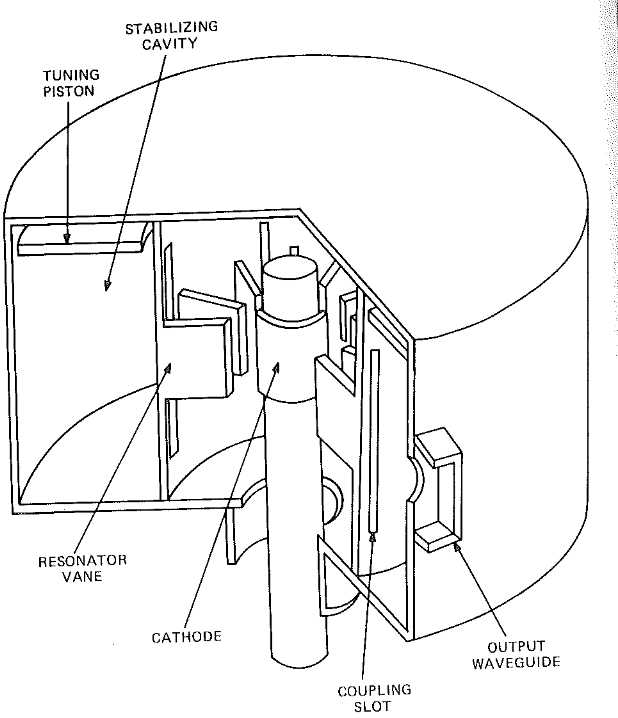


Fig. 14. Principle of the coaxial magnetron

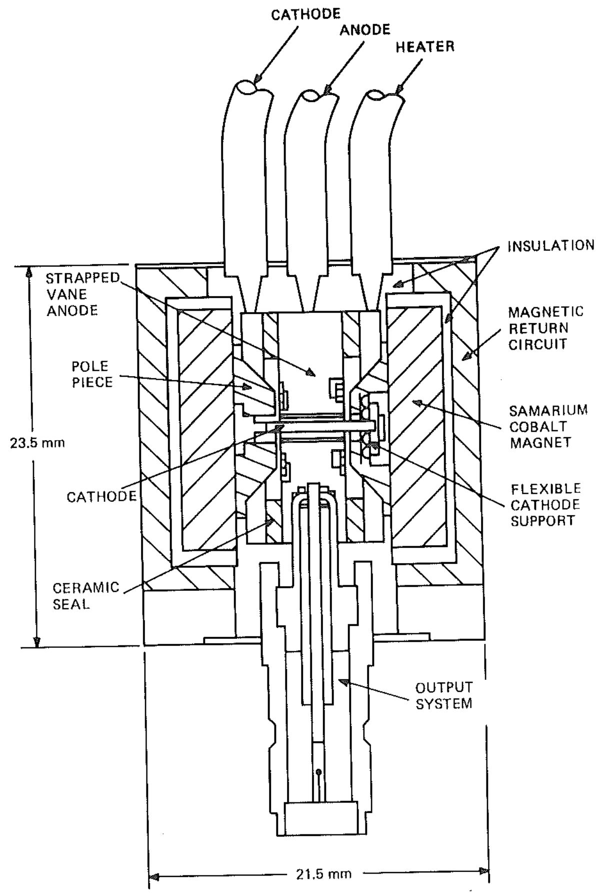


Fig. 15. Cross-section of 3 cm rugged magnetron

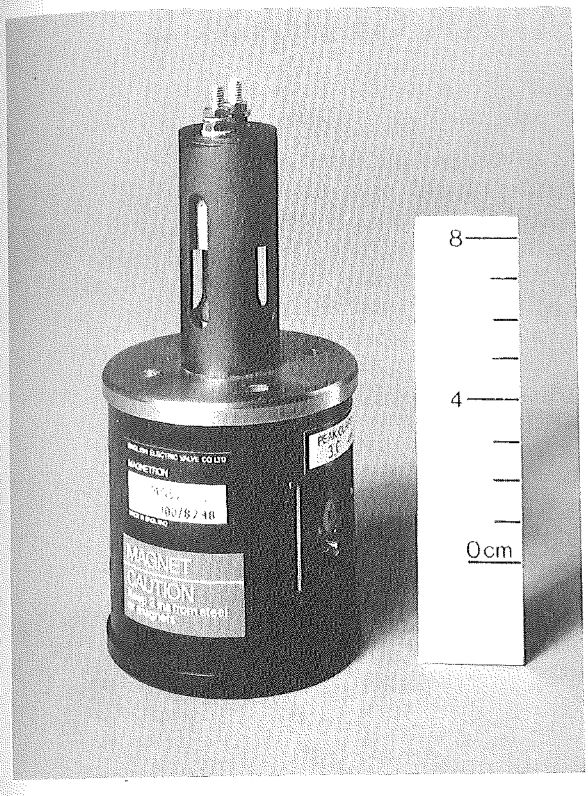


Fig. 16. Magnetron for 3.3 mm wavelength

CONCLUSION

In this very brief summary of the evolution of the magnetron from its chance birth in 1921 to its becoming the key component in many systems, the technologies of construction have been taken for granted. However, the huge effort applied to these technologies, both for magnetrons and other microwave devices, has ensured that the continually refined systems requirements can be met.

For example, insulator materials and technology have been developed to withstand the high voltage stresses involved, to hold components in their required relative position, to conduct heat away, and to enable the high microwave power densities to be transmitted with minimum loss.

Since the cathode is subject to significant electron bombardment, thermionic emission is not usually a problem, though design for adequate cooling is necessary. However the possibility of arcing due to high voltage stress at the surface leads to the need for a rugged surface.

The use of permanent magnet materials of high performance in 'package' structures has led to much ingenuity in integrating these with the rest of the valve elements to enable both electrical and mechanical performance needs to be met.

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